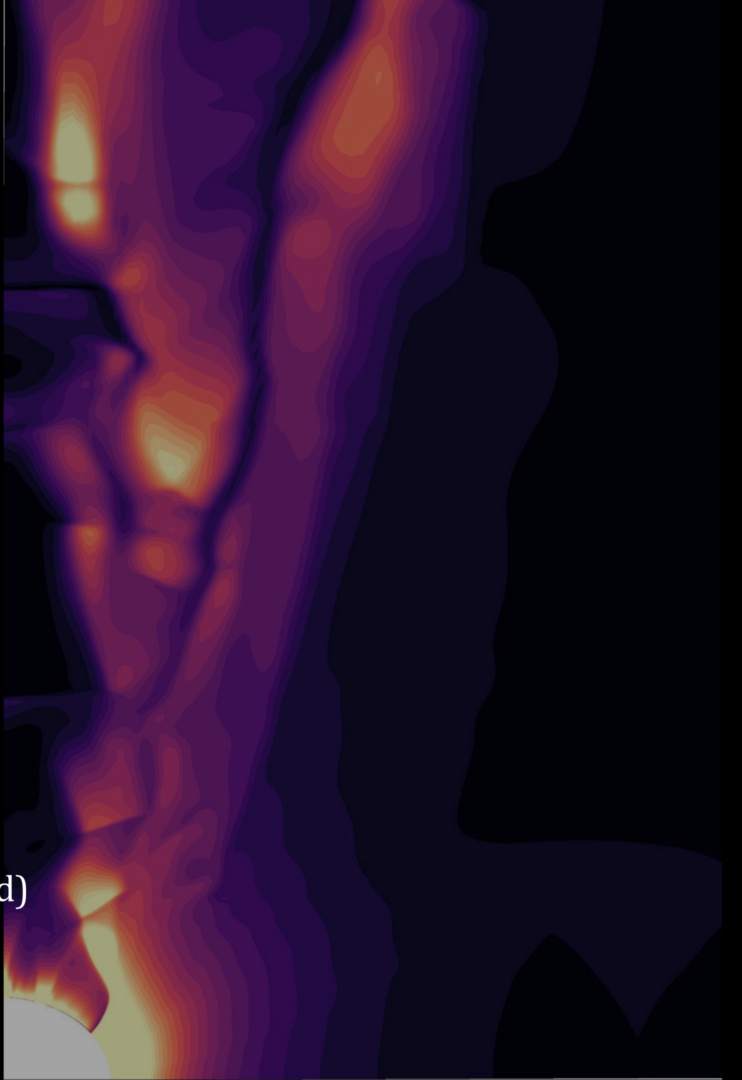
Oscillating Advective Viscous Accretion Disk: Dynamical properties from the Hydrodynamic simulations

Presented by,
Mr. Sanjit Debnath
ARIES, India

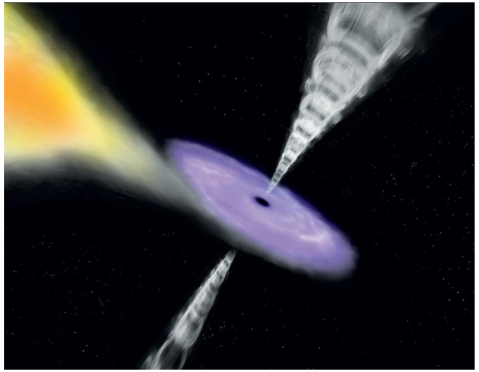
आर्यभट्ट प्रेक्षण विज्ञान शोध संस्थान
Aryabhatta Research Institute of Observational Sciences

Working with,
Dr. Indranil Chattopadhyay (ARIES, India)
Dr. Raj Kishore Joshi (Nicolaus Copernicus Astronomical Center, Poland)



Accretion physics

- X-ray binaries and AGNs show distinct spectral and temporal changes across energy bands.
- Systems like wind-fed binaries, Sgr A*, and M87 can be explained by low-angular-momentum transonic advective accretion flows.
- QPOs from stellar-mass black holes and Sgr A* flares may arise from oscillatory shocks in low-angular-momentum flows (Molteni et al. 1996; Chakrabarti et al. 2008).

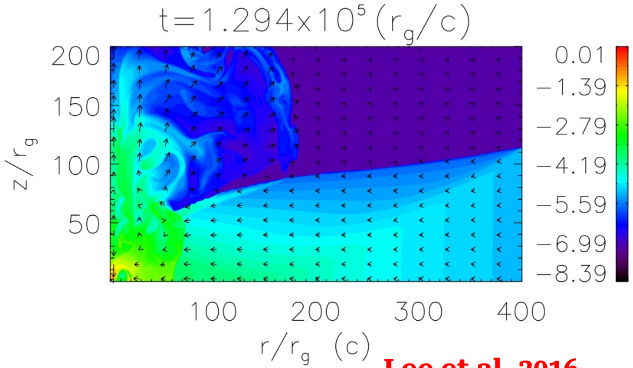


Artist's impression of black hole binary
Image credit: ESA/ATG medialab

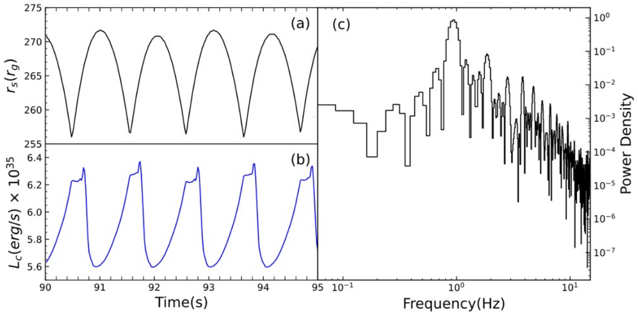
Shock in the Accretion Disc

- Various simulations (Lanzafame et al. 1998; Das et al. 2014; Lee et al. 2011; Giri et al. 2015; Lee et al. 2016) have indicated that viscosity could initiate shock oscillations.

- Focusing on the shock oscillation model, Debnath et al. (2024) shown how viscosity can trigger shock oscillation and get wide range (sub-Hz to 10s Hz) of QPOs using 1D code.



Lee et al. 2016



Debnath et al. 2024

Model To Study

- We examine effect of viscosity along with cooling.
- Three models: L1, L2, and L3.
- viscosity parameter α = 0.002, 0.005, 0.01, 0.025, 0.05

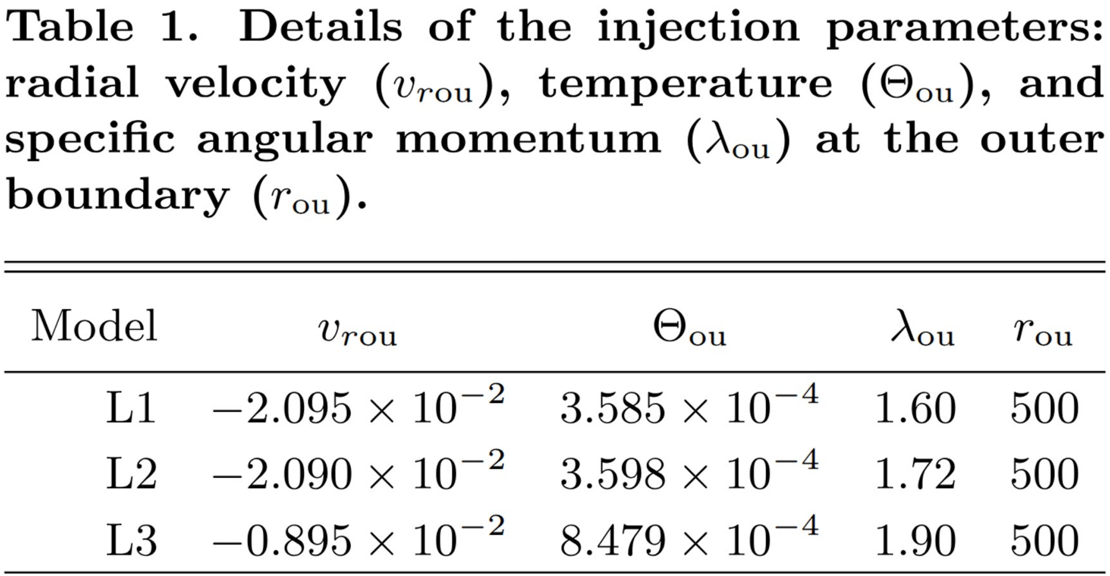
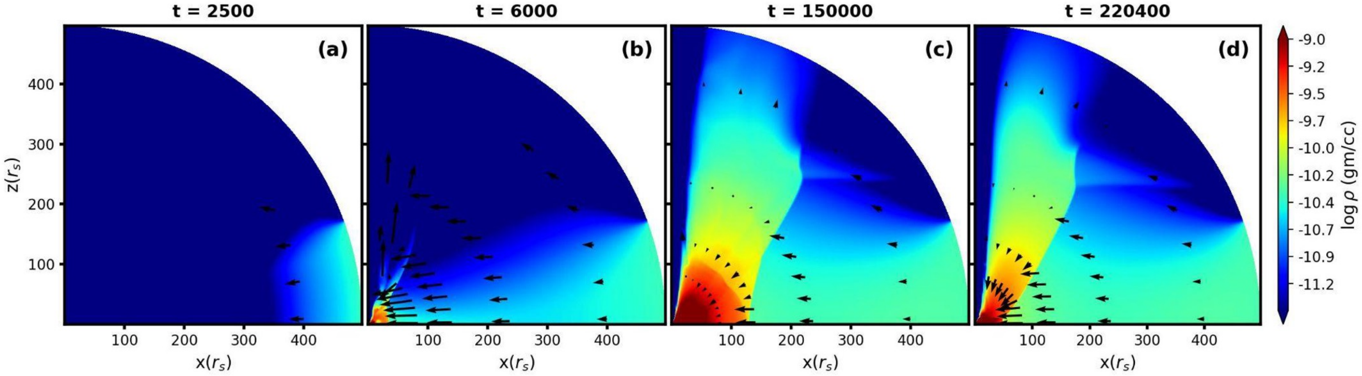


Table 1. **Details of the injection parameters: radial velocity (v_{rou}), temperature ($\Theta_{\rm ou}$), and specific angular momentum ($\lambda_{\rm ou}$) at the outer boundary ($r_{\rm ou}$).**

Model	v_{rou}	$\Theta_{\rm ou}$	$\lambda_{\rm ou}$	$r_{\rm ou}$
L1	-2.095×10^{-2}	3.585×10^{-4}	1.60	500
L2	-2.090×10^{-2}	3.598×10^{-4}	1.72	500
L3	-0.895×10^{-2}	8.479×10^{-4}	1.90	500

Initial set-up

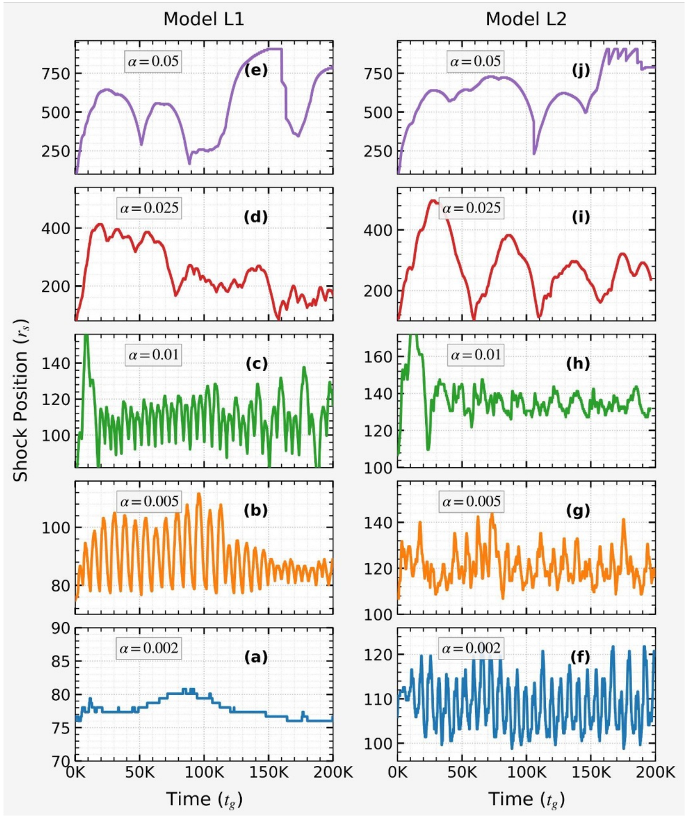
- ❑ We evaluate the outer boundary values using steady state solution presented in the work Debnath et al. (2024).
- ❑ Below is the Inviscid accretion flow for model L1.



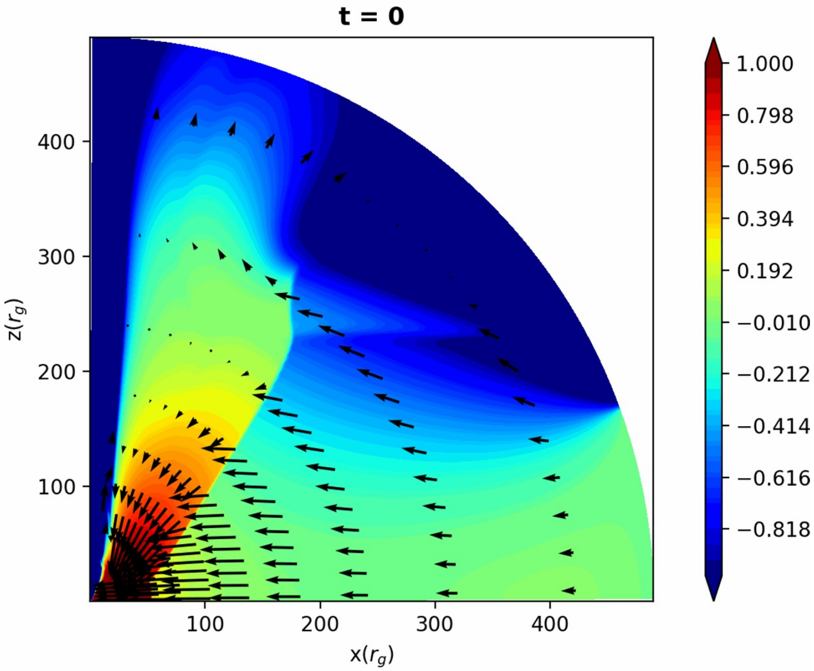
This quasi-stable disk serves as the initial setup

RESULTS: Oscillating Shocks

- ➔ Shock oscillations are dictated by the balance between centrifugal force, pressure gradients, and gravity.
- ➔ Critical viscosity for oscillation is different for different model.
- ➔ Higher the viscosity ➡ More irregular oscillation.

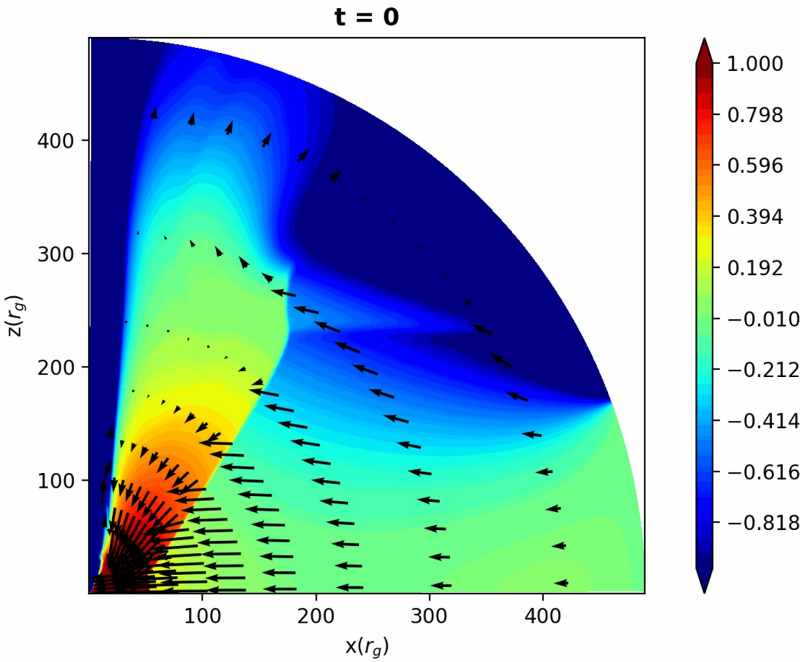


RESULTS: Oscillating Shocks



$\alpha = 0.025$

Model L2

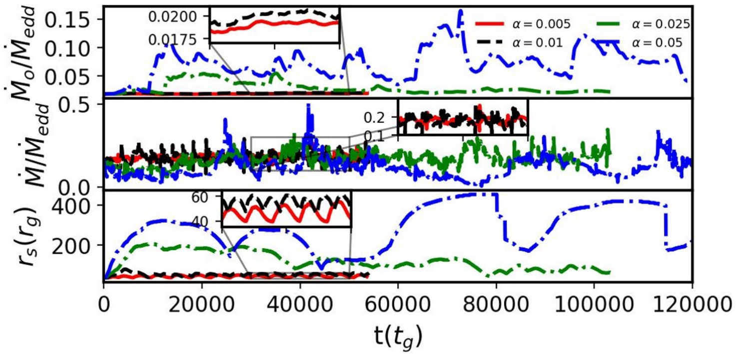


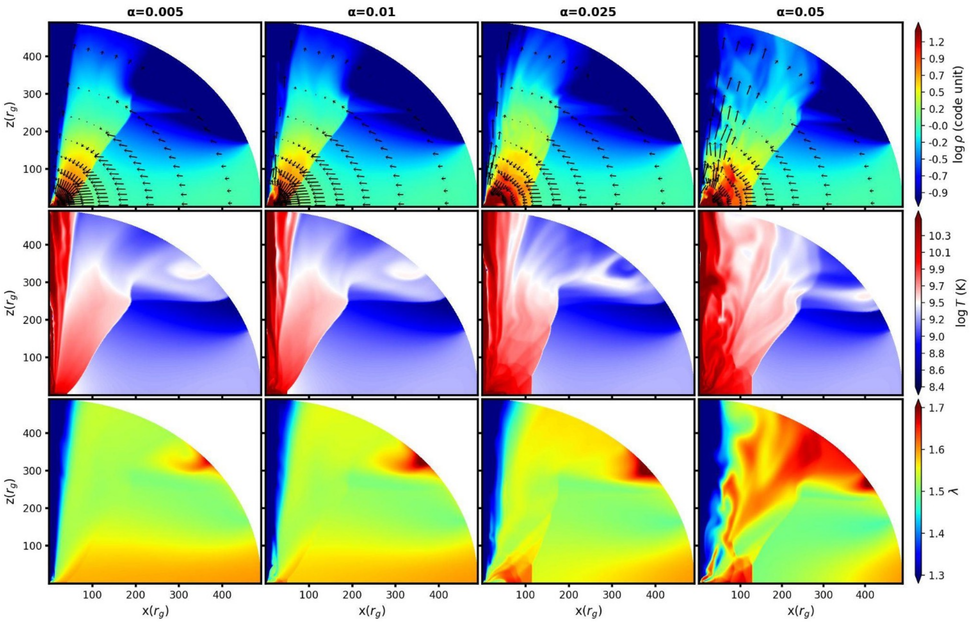
$\alpha = 0.05$

RESULTS: Oscillating Shocks

At dynamical time, t = 50000 t_g for model L1.

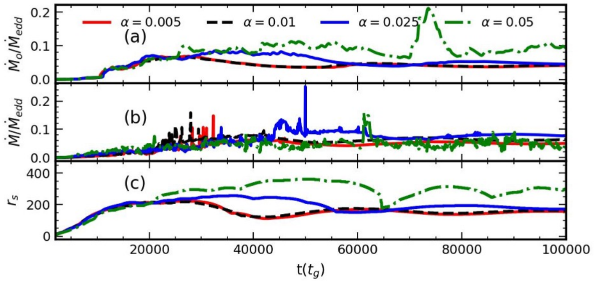
For higher viscosity, the outer shock moves outward.

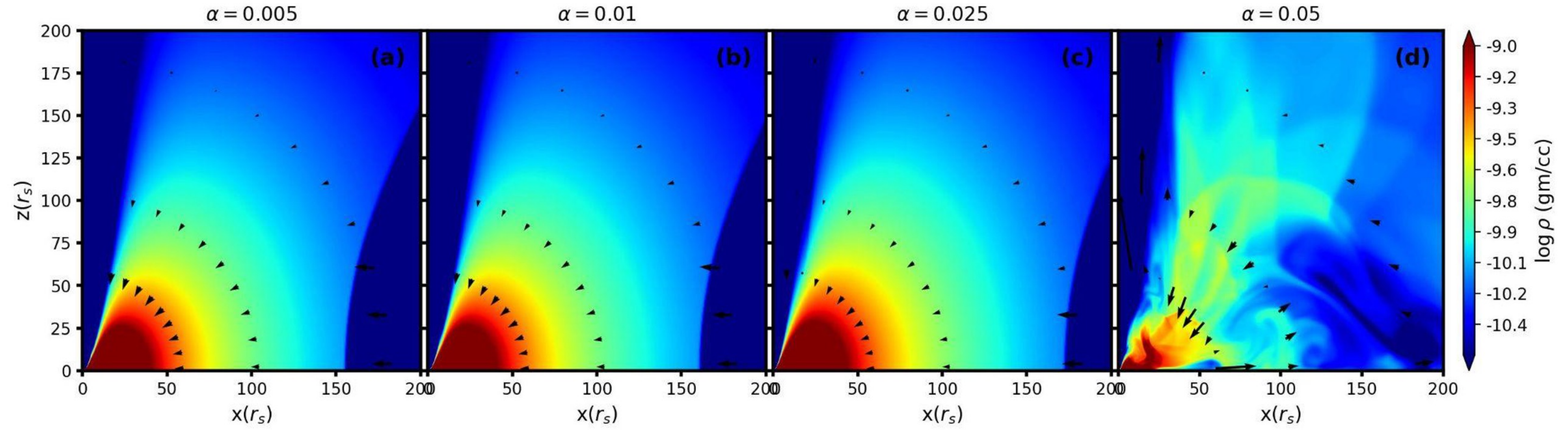




RESULTS: Torus formation

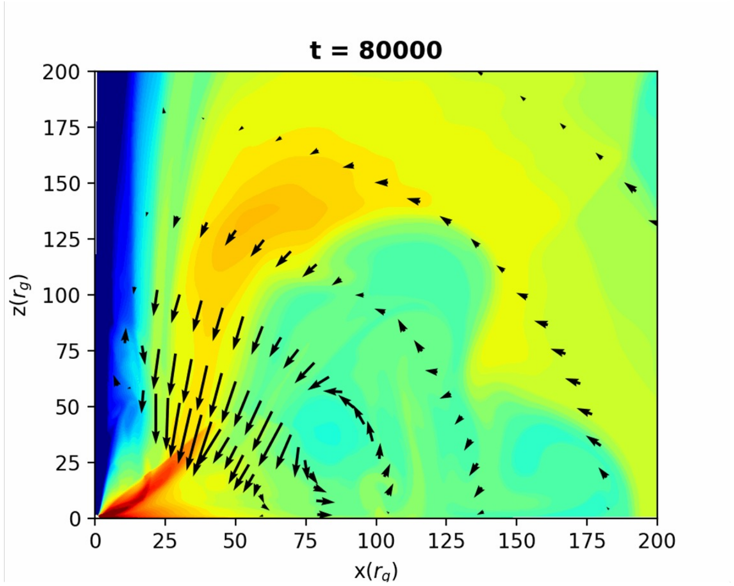
- Model L3, with $\alpha = 0.005, 0.01, 0.025$ form accreting torus in post shock disc with outflow.
- But with high $\alpha = 0.05$, due to backflow turbulence, no torus like accretion.



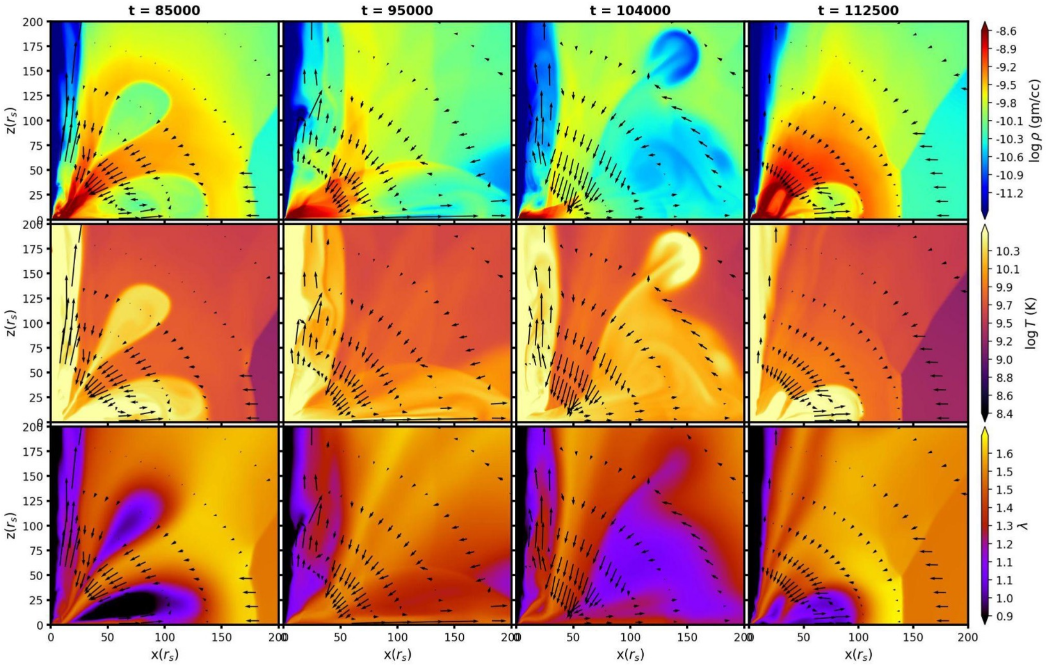


RESULTS: Turbulence

Model L1, α = 0.05



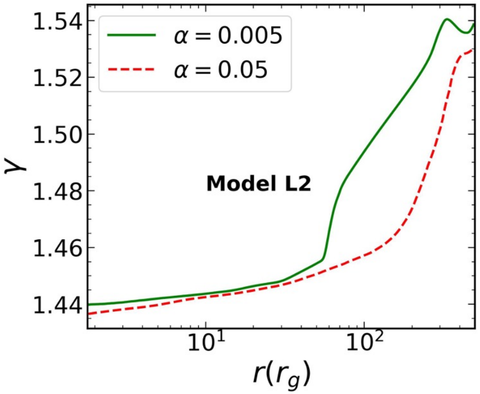
Density(ρ)

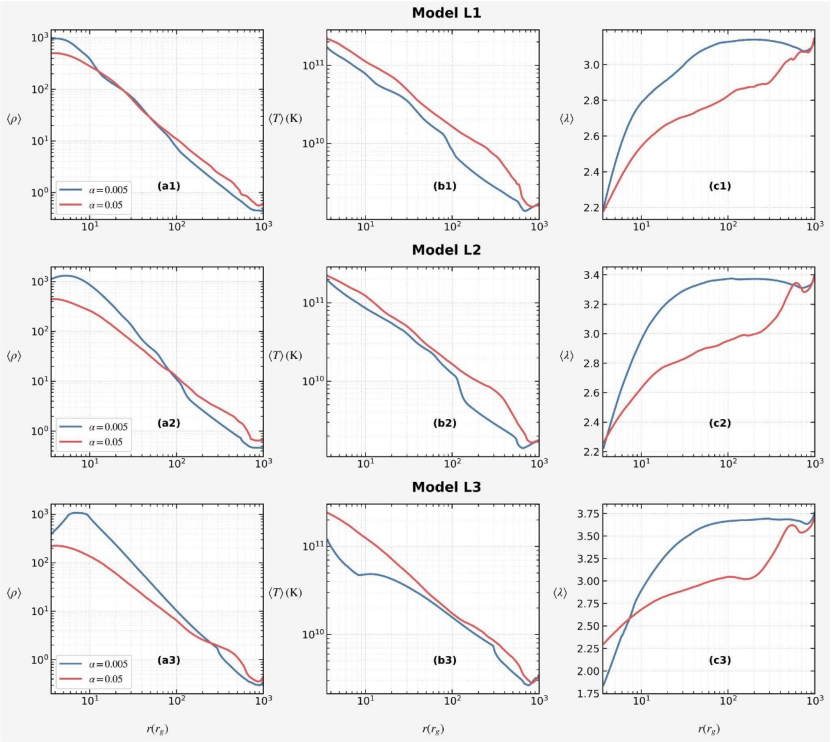


RESULTS: Time & Angle Average Flows

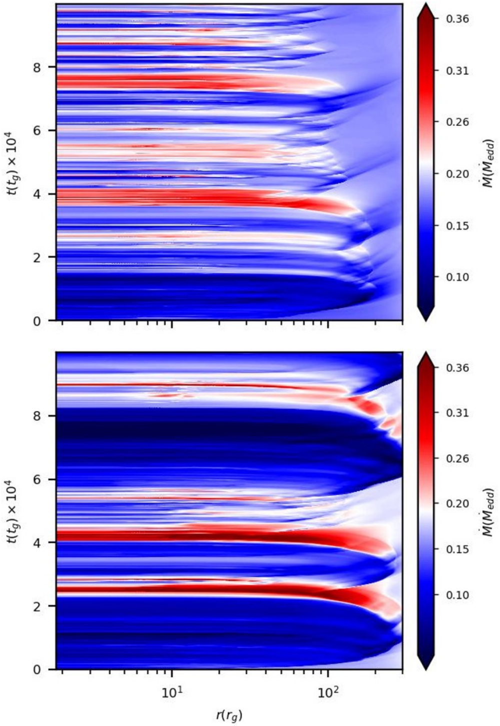
Time and angle averaged radial profile of flow.

The power-law indices (1.1 -1.4) deviate from ADAF predictions (1.5) (Narayan & Yi 1995), but match those from outflow-driven models (Blandford & Begelman 2004).



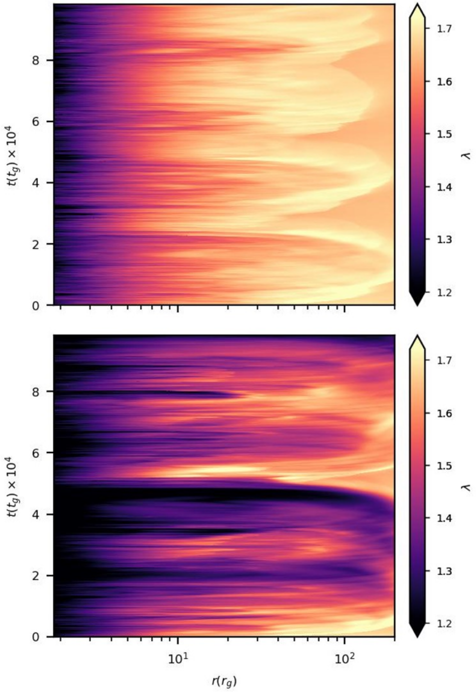


RESULTS: Time-series Analysis



α = 0.025

α = 0.05



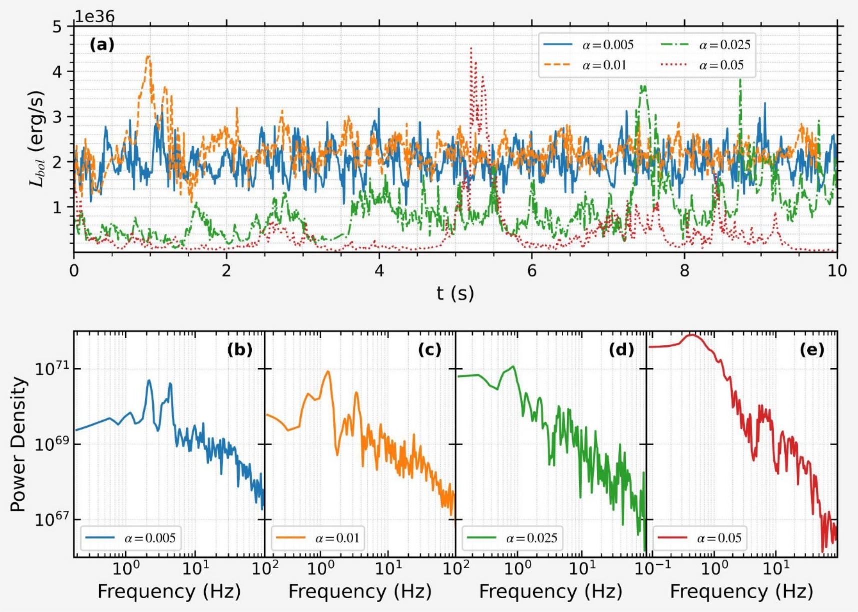
Space time diagram of accretion rate for model L2

Space time diagram of angular momentum for model L2

RESULTS: Time-series Analysis

Synthetic light curves for model L2 considering bremsstrahlung and synchrotron radiation.

We consider a black hole mass of M_{bh} = $10M_{\odot}$, accretion rate of 0.3 M_{edd}.

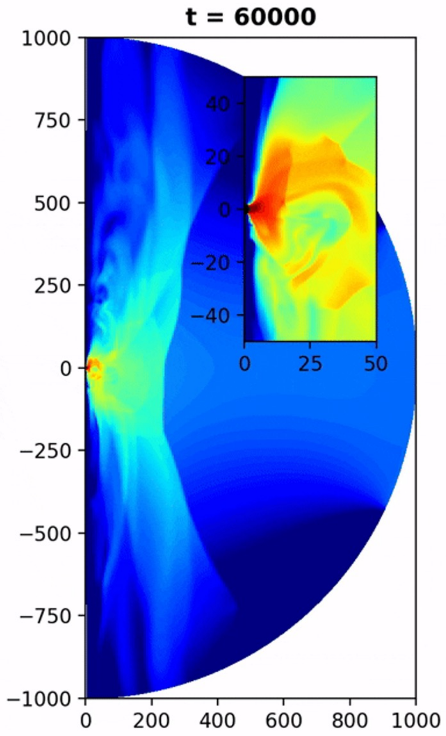


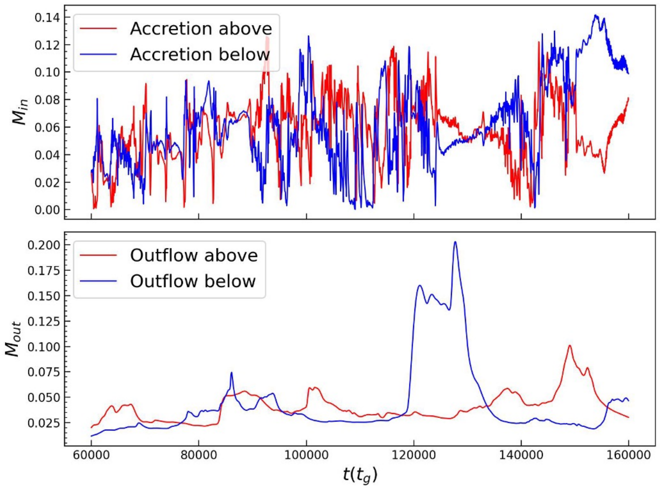
PSD shows frequency 2.2 Hz, 1.30 Hz, 0.85 Hz, 0.44 Hz

RESULTS: Time Evolution

Asymmetric hot bubble and outflow from the disk.

This work is currently in progress



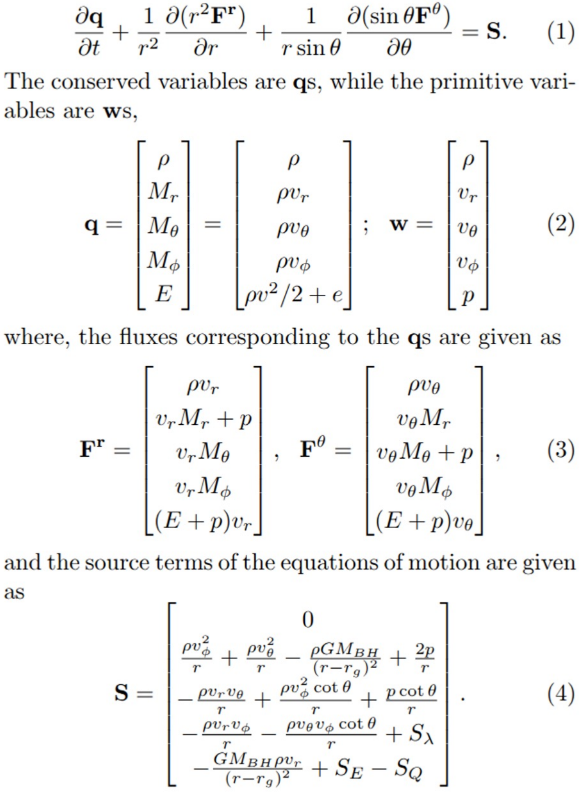


Summary

- ➔ Viscosity cause the post-shock disc to oscillate and can produce multiple shocks, leading to periodic outflows.
- ➔ As the shock moves outward with increasing viscosity, the oscillation time scale becomes longer, resulting in low-frequency QPOs.
- ➔ Higher viscosity can generate turbulence bubble. Outward motion of bubbles along the equatorial plane is thwarted by the mass accretion rate, but those along the axis leave the domain as outflow.
- ➔ Angle and time averaging smooth the accretion profiles, reducing shock-induced jumps, but they still differ from the ADAF profile.

THANK YOU !

Backup: Equation of motion



$$\frac{\partial \mathbf{q}}{\partial t} + \frac{1}{r^2}\frac{\partial (r^2 \mathbf{F}^{\mathbf{r}})}{\partial r} + \frac{1}{r\sin\theta}\frac{\partial (\sin\theta \mathbf{F}^{\theta})}{\partial \theta} = \mathbf{S}. \qquad (1)$$

The conserved variables are **q**s, while the primitive variables are **w**s,

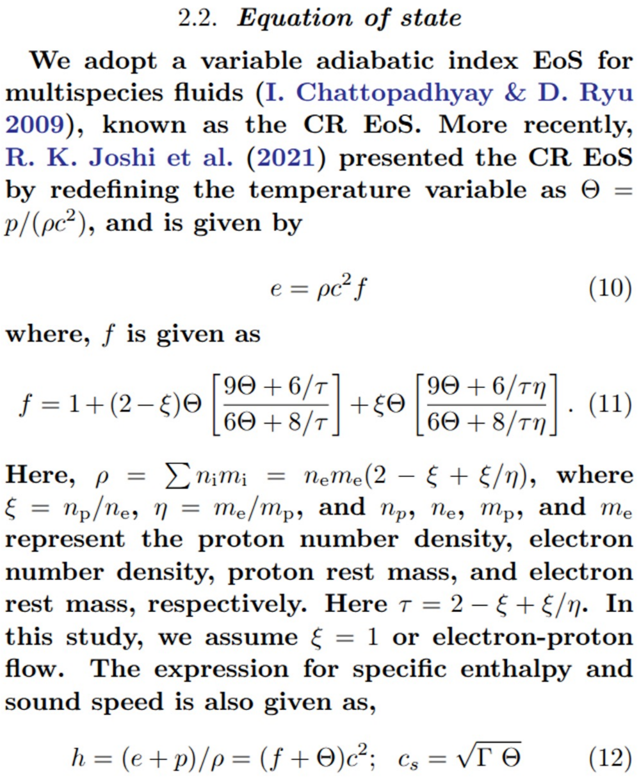
$$\mathbf{q} = \begin{bmatrix} \rho \\ M_r \\ M_\theta \\ M_\phi \\ E \end{bmatrix} = \begin{bmatrix} \rho \\ \rho v_r \\ \rho v_\theta \\ \rho v_\phi \\ \rho v^2/2 + e \end{bmatrix} ; \quad \mathbf{w} = \begin{bmatrix} \rho \\ v_r \\ v_\theta \\ v_\phi \\ p \end{bmatrix} \qquad (2)$$

where, the fluxes corresponding to the **q**s are given as

$$\mathbf{F}^{\mathbf{r}} = \begin{bmatrix} \rho v_r \\ v_r M_r + p \\ v_r M_\theta \\ v_r M_\phi \\ (E+p) v_r \end{bmatrix} , \quad \mathbf{F}^{\theta} = \begin{bmatrix} \rho v_\theta \\ v_\theta M_r \\ v_\theta M_\theta + p \\ v_\theta M_\phi \\ (E+p) v_\theta \end{bmatrix} , \qquad (3)$$

and the source terms of the equations of motion are given as

$$\mathbf{S} = \begin{bmatrix} 0 \\ \frac{\rho v_\phi^2}{r} + \frac{\rho v_\theta^2}{r} - \frac{\rho G M_{BH}}{(r-r_g)^2} + \frac{2p}{r} \\ -\frac{\rho v_r v_\theta}{r} + \frac{\rho v_\phi^2 \cot\theta}{r} + \frac{p\cot\theta}{r} \\ -\frac{\rho v_r v_\phi}{r} - \frac{\rho v_\theta v_\phi \cot\theta}{r} + S_\lambda \\ -\frac{G M_{BH} \rho v_r}{(r-r_g)^2} + S_E - S_Q \end{bmatrix} . \qquad (4)$$



2.2. *Equation of state*

We adopt a variable adiabatic index EoS for multispecies fluids (I. Chattopadhyay & D. Ryu 2009), known as the CR EoS. More recently, R. K. Joshi et al. (2021) presented the CR EoS by redefining the temperature variable as $\Theta = p/(\rho c^2)$, and is given by

$$e = \rho c^2 f \qquad (10)$$

where, f is given as

$$f = 1 + (2-\xi)\Theta\left[\frac{9\Theta + 6/\tau}{6\Theta + 8/\tau}\right] + \xi\Theta\left[\frac{9\Theta + 6/\tau\eta}{6\Theta + 8/\tau\eta}\right]. \qquad (11)$$

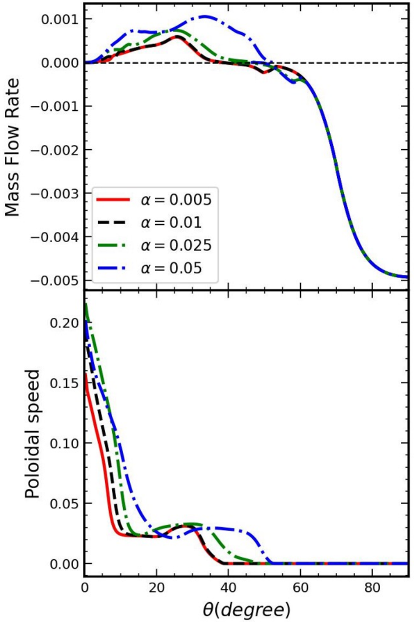
Here, $\rho = \sum n_{\rm i} m_{\rm i} = n_{\rm e} m_{\rm e}(2 - \xi + \xi/\eta)$, where $\xi = n_{\rm p}/n_{\rm e}$, $\eta = m_{\rm e}/m_{\rm p}$, and $n_{\rm p}$, $n_{\rm e}$, $m_{\rm p}$, and $m_{\rm e}$ represent the proton number density, electron number density, proton rest mass, and electron rest mass, respectively. Here $\tau = 2 - \xi + \xi/\eta$. In this study, we assume $\xi = 1$ or electron-proton flow. The expression for specific enthalpy and sound speed is also given as,

$$h = (e+p)/\rho = (f+\Theta)c^2; \quad c_s = \sqrt{\Gamma\,\Theta} \qquad (12)$$

Backup: RESULTS: Outflow properties

θ-dependence of the time -averaged mass fluxes and poloidal velocity of outflow at r = 400 rg

MODEL L1



Time-averaged radial distribution of the kinetic energy flux (in unit $\dot{M}_{bh}c^2$) and the momentum flux (in unit $\dot{M}_{bh}c$) for the outflows.

α = 0.05